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Impact of a permanent El Niño (El Padre) and Indian Ocean Dipole in warm Pliocene climates

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[1] Pliocene sea surface temperature data, as well as terrestrial precipitation and temperature proxies, indicate warmer than modern conditions in the eastern equatorial Pacific and imply permanent El Niño–like conditions with impacts similar to those of the 1997/1998 El Niño event. Here we use a general circulation model to examine the global-scale effects that result from imposing warm tropical sea surface temperature (SST) anomalies in both modern and Pliocene simulations. Observed SSTs from the 1997/1998 El Niño event were used for the anomalies and incorporate Pacific warming as well as a prominent Indian Ocean Dipole event. Both the permanent El Niño (also called El Padre) and Indian Ocean Dipole (IOD) conditions are necessary to reproduce temperature and precipitation patterns consistent with the global distribution of Pliocene proxy data. These patterns may result from the poleward propagation of planetary waves from the strong convection centers associated with the El Niño and IOD.

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1. Introduction

[2] The mid-Piacenzian Age of the Pliocene Epoch (3.3–3.0 Ma) is the most recent warm interval in which climatic forcings, solar luminosity and atmospheric carbon dioxide concentrations were similar to modern conditions [e.g., *Raymo et al.*, 1996; *Dowsett et al.*, 1999]. There is evidence for warmer high-latitude sea surface temperatures (SSTs) [*Dowsett et al.*, 1992, 2009], a lack of northern hemisphere land ice, and increased sea levels [*Dowsett and Cronin*, 1990; *Jansen and Sjoholm*, 1991], all of which may have contributed to warmer climatic conditions than present, despite the similarity in forcings. Indeed, various modeling studies suggest that the global Pliocene climate may have been warmer than the modern by an average of 2–3°C [e.g., *Jansen and Sjoholm*, 1991; *Sloan et al.*, 1996; *Haywood et al.*, 2000; *Haywood and Valdes*, 2004].

[3] It is still largely uncertain, however, how this warmth was generally maintained throughout the interval. Recently derived sea surface temperature (SST) data, using alkenone paleothermometry techniques, suggest that the tropical Pacific west-east temperature gradient may have been less prominent than today [*Wara et al.*, 2005; *Ravelo et al.*, 2006]. This condition may have contributed to altered atmospheric circulation patterns, northern latitude teleconnections, and overall climatic impacts similar to a permanent El Niño–like state [*Haywood et al.*, 2005; *Ravelo et al.*, 2006], which we call here an El Padre as per *Ravelo*'s [2008] definition.

[4] Many lines of evidence indicate that high-latitude warming in the Pliocene was substantial, and the forces that sustained that warmth are not fully understood. However, even accepting the high-latitude warming as an equilibrium condition is not sufficient in GCM simulations to explain all regional climate changes. If an El Padre state did exist during the Pliocene, it may have contributed to the warm global climate, just as the modern El Niño tends to alter temperature and precipitation in some regions and raise global average temperatures during its peak [*Wara et al.*, 2005; *Ravelo et al.*, 2006]. Here we use an atmospheric GCM, forced with warm (relative to modern) eastern equatorial Pacific SSTs, to determine whether an El Padre state, in combination with a dipole SST pattern in the tropical Indian Ocean, and the resulting teleconnections, could have contributed to a global climate warming similar to that observed in the geologic record.

2. Previous Work

2.1. Paleoclimate Proxy Data for Sea Surface Temperature Reconstructions

[5] Paleoclimate proxy data derived from open ocean core samples and land sections suggested warmer than expected SSTs in the North Atlantic during the Pliocene [*Dowsett and Poore*, 1991; *Dowsett et al.*, 2009; *Williams et al.*, 2009]. To explore this phenomenon, the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project, and its successor, PRISM2, were created to produce a comprehensive reconstruction of a mid-Piacenzian Age Pliocene time "slab," from 3.3 to 3.0 Ma, from relatively abundant proxy data [*Dowsett and Poore*, 1991; *Dowsett et al.*, 1999].

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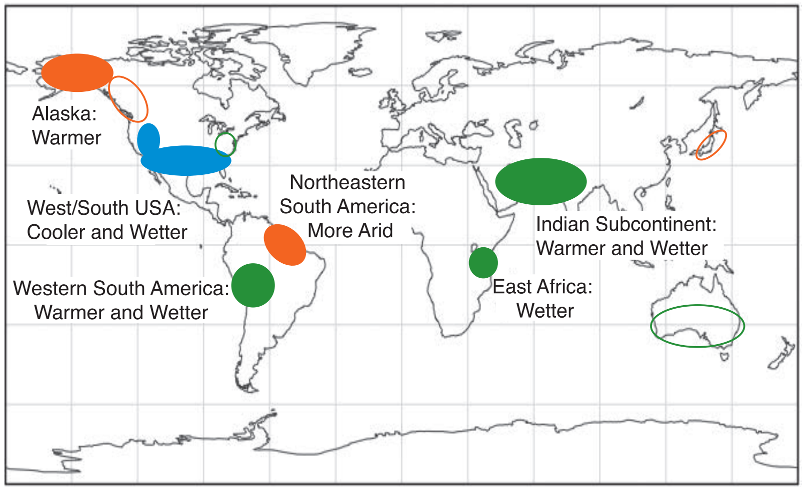

Figure 1. El Niño–like climate impacts suggested by Pliocene climate proxy data.

[6] PRISM2 provided SST reconstructions for the Pliocene time slab using estimates based on quantitative and qualitative faunal analyses of marine microfossils [*Dowsett et al.*, 1999]. The data compiled from 77 globally distributed marine sites suggest that high-latitude SSTs were warmer by approximately 6°C [*Dowsett et al.*, 1999]. However, PRISM2 data did not include many data points from tropical oceans, specifically the tropical Atlantic and eastern tropical Pacific [*Dowsett*, 2007a]. To better assess the role of the tropical oceans in the Pliocene, *Wara et al.* [2005] and *Ravelo et al.* [2006] derived new tropical SST reconstructions using alkenone paleothermometry, which utilizes carbon isotopic measurements of chains of organic phytoplankton biomarkers (alkenones) as SST and productivity indicators [*Haywood et al.*, 2005; *Wara et al.*, 2005; *Ravelo et al.*, 2006]. They found a persistent pattern of warmer SSTs at low latitudes, specifically in the eastern tropical Pacific, and suggest that a reduced the W–E SST gradient existed in the tropical Pacific. *Wara et al.* [2005] interpreted these measurements as a "permanent El Niño" SST pattern throughout the Pliocene. Additional multiproxy data sets collected from both the eastern and western tropical Pacific appear to support a persistent decreased tropical sea surface temperature gradient [*Dowsett*, 2007b; *Dowsett and Robinson*, 2009].

[7] This "permanent El Niño" hypothesis prompted *Molnar and Cane* [2007] to evaluate the correlation between the Pliocene regional terrestrial climate proxy data and the climate impacts of modern El Niño events. They found that the 1997/1998 El Niño yielded the greatest similarity in temperature and rainfall to the Pliocene terrestrial geologic record (Figure 1) [*Molnar and Cane*, 2002, 2007]. This particular event was characterized by the classic El Niño warming of the eastern equatorial Pacific, as well as a pattern of warmer SSTs in the western Indian Ocean and cooler SSTs in the eastern part of the basin called the Indian Ocean Dipole (IOD). Hereafter, we refer to an "IOD/El Padre" to describe this combination of SST features, in part for its likeness to the SST pattern during an El Niño event, but also to distinguish it from the episodic and transient character of a true El Niño, and to acknowledge the added IOD feature.

2.2. Pliocene Modeling Studies and Implications

[8] Since an El Padre condition has been suggested as a possibility for our future climate [*Trenberth et al.*, 2007; *Vecchi and Soden*, 2007], several modeling efforts have focused on understanding tropical warming mechanisms operating during the Pliocene and their possible contribution to global warmth. Each of these studies has taken a different approach to evaluating the physical impact of elevated tropical SSTs, and consequently, each study has come to a different conclusion regarding the role of the tropics in driving warmth in the Pliocene.

[9] Using the HadCM3, a fully coupled ocean-atmosphere GCM, *Haywood and Valdes* [2004] and *Haywood et al.* [2005] performed sensitivity tests showing that estimated CO_2 forcing at levels similar to those of the Pliocene would lead to warmer tropics, and that cryosphere feedbacks alone could not account for all the temperature and precipitation patterns seen in the Pliocene data. They also suggested that alkenone-derived tropical SSTs were more consistent with their model results, even though the alkenone SST values in the tropics are all from upwelling regions and may not be representative of the broader tropical changes.

[10] *Barreiro et al.* [2006] used an atmosphere-only GCM to investigate the role that warmer tropical SSTs may have played in altering atmospheric circulation in extratropical regions. Their initial hypothesis suggested that a lack of cool, upwelling waters in the eastern tropical Pacific would reduce the low-level cloud cover, allowing more solar radiation to reach the surface waters. With surface waters warming even more, atmospheric water vapor would increase, acting as a positive feedback to the warming climate. Using tropical SST data to drive simulations with the GFDL AM2 atmospheric model, they found that a breakdown of the W–E temperature gradient in the tropical Pacific led to the formation of two intertropical convergence regions (ITCZs) north and south of the equator. The appearance

of the second ITCZ allows the ocean to accumulate more freshwater in the eastern tropical Pacific, which normally has an excess of evaporation. *Barreiro et al.* [2006] also found that the Walker circulation collapsed in the absence of the W–E tropical Pacific SST gradient, resulting in the reduced low-level stratus cloud cover they had hypothesized. Subsequent changes in atmospheric circulation yielded a warming over North America, which may have been a factor in keeping the northern latitudes ice free. *Barreiro et al.* [2006] thus conclude that significant climatic patterns during the Pliocene were consistent with the warmer tropical SSTs indicated by Pliocene paleoceanographic data.

[11] *Fedorov et al.* [2006] approached the warm Pliocene question by attempting to determine how changes to the evaporation/precipitation balance in the tropics, as well as changes to the thermocline depth due to heat fluxes, could have maintained warmer tropical SSTs specified by Pliocene paleoceanographic data. They accepted warmer tropical SST data as valid at the outset, and focused on analyzing the output from an ocean-only GCM, an atmosphere-only GCM forced with warm tropical SSTs, and coupled GCM simulations, in order to understand how warming in the tropics could be maintained. In assessing the various simulation results, they suggested that the transport of moisture from warmer tropical regions helps sustain warm high-latitude SSTs. These in turn are mostly responsible for driving global Pliocene warmth, providing a positive feedback that keep the tropics warm [*Crowley*, 1991; *Sloan et al.*, 1996; *Fedorov et al.*, 2006]. Reduced oceanic heat loss to the atmosphere during these times can also induce a deepening of the thermocline and a movement toward permanent El Niño–like conditions [*Fedorov et al.*, 2006]. However, this is only possible when long timeframes permit the tropical oceans to adjust to high-latitude alterations. Like *Barreiro et al.* [2006], *Fedorov et al.* [2006] maintained that the collapse of the Walker circulation led to decreased high-level reflective cloud cover and planetary albedo, and increased atmospheric water vapor through permanent El Niño–like conditions. These two effects were thus suggested as the primary contributors to warmer conditions during the Pliocene.

[12] In a separate study, *Haywood et al.* [2007] used a fully coupled ocean/atmosphere model to examine whether sustained tropical warming and contributions to overall Pliocene warmth would be feasible using reconstructed Pliocene vegetation and ice sheet distributions [PRISM 2]. *Haywood et al.* [2005] had previously asserted that early PRISM findings showing no change in tropical SSTs [*Dowsett et al.*, 1994] were inconsistent with model results indicating that the tropics should have warmed as well. In their 2007 study, *Haywood et al.* [2007] found that a permanent El Niño–like state was not predicted under Pliocene boundary conditions using the HadCM3 coupled atmosphere-ocean climate model. Temperature increases in the eastern equatorial Pacific were minimal and warming was also produced in the western equatorial Pacific, maintaining a significant W–E temperature gradient. Additionally, when a prescribed permanent El Niño–like condition was imposed during sensitivity tests, mean surface temperatures increased by just 0.6°C compared to the 2–3°C warming expected from proxy data. Since their results could not reproduce a permanent El Niño under Pliocene boundary conditions, and citing differing interpretations of Mg/Ca-derived Pacific SST records [*Wara et al.*, 2005; *Rickaby and Halloran*, 2005], *Haywood et al.* [2007] questioned the possible contribution of a permanent El Niño–like condition to Pliocene global warmth.

[13] The HadCM3 has a cool bias in the central tropical Pacific and a warm bias over the maritime continent [*Haywood et al.*, 2007] making it difficult for this model to obtain a permanently decreased SST gradient, like that of the El Padre. This makes it unlikely to reproduce the associated large-scale teleconnections, which can be distinct from those generated by El Niños. Intercomparisons of coupled model results with terrestrial proxy data show that we still do not fully understand all the complex air-sea interactions associated with much warmer climates. However, coupled O-A GCMs are necessary to help provide the physical understanding for regional paleoclimatic environments, such as those of the warm Pliocene, that are difficult to obtain from scattered proxy data alone.

[14] However, new SST data from the equatorial Pacific ocean, derived from faunal and alkenone paleothermometry, have again strengthened the argument in favor of a permanent El Niño, or El Padre, during the Pliocene [*Ravelo et al.*, 2006; *Ravelo*, 2008; *Dowsett and Robinson*, 2009]. Given these data, and the expectation that increased tropical warmth should produce impacts further afield [*Molnar and Cane*, 2007], we have chosen to reexamine the issue of Pliocene warming but from a new perspective. In this study, we explore the general relationship between warmer tropical SSTs and extratropical climate patterns without making a priori assumptions about the validity of Pliocene proxy-derived tropical SST data, using the 1997/1998 El Niño/IOD SST distributions as a forcing.

3. Testing Tropical SST Contributions to Pliocene Warmth

[15] The previous inconsistent modeling results leave the exact role of the tropical contribution to Pliocene warmth largely undetermined. In this study we have run climate simulations using an IOD/El Padre anomalous SST distribution, and assess the possible contribution of the anomalous SSTs to mid-Piacenzian warmth by comparing our results to paleoclimate proxy data for the Pliocene. We ran a total of five simulations (see Table 1) to equilibrium. Modern Control (ModControl) serves as our control run, and utilizes observed monthly climatological specified SSTs. Pliocene Control (PlioControl) is the "background" state of the Pliocene that is forced only by PRISM2 SST, vegetation and ice sheet reconstructions. The Modern IOD/El Padre (ModPadre) and Pliocene IOD/El Padre (PlioPadre) simulations test the IOD/El Padre condition both in the context of the modern and Pliocene climates. To produce the IOD/El Padre feature in ModPadre and PlioPadre, we added the tropical (16°N to 16°S) SST anomalies from November 1997 to the modern monthly climatology and the PRISM2 SST reconstruction,

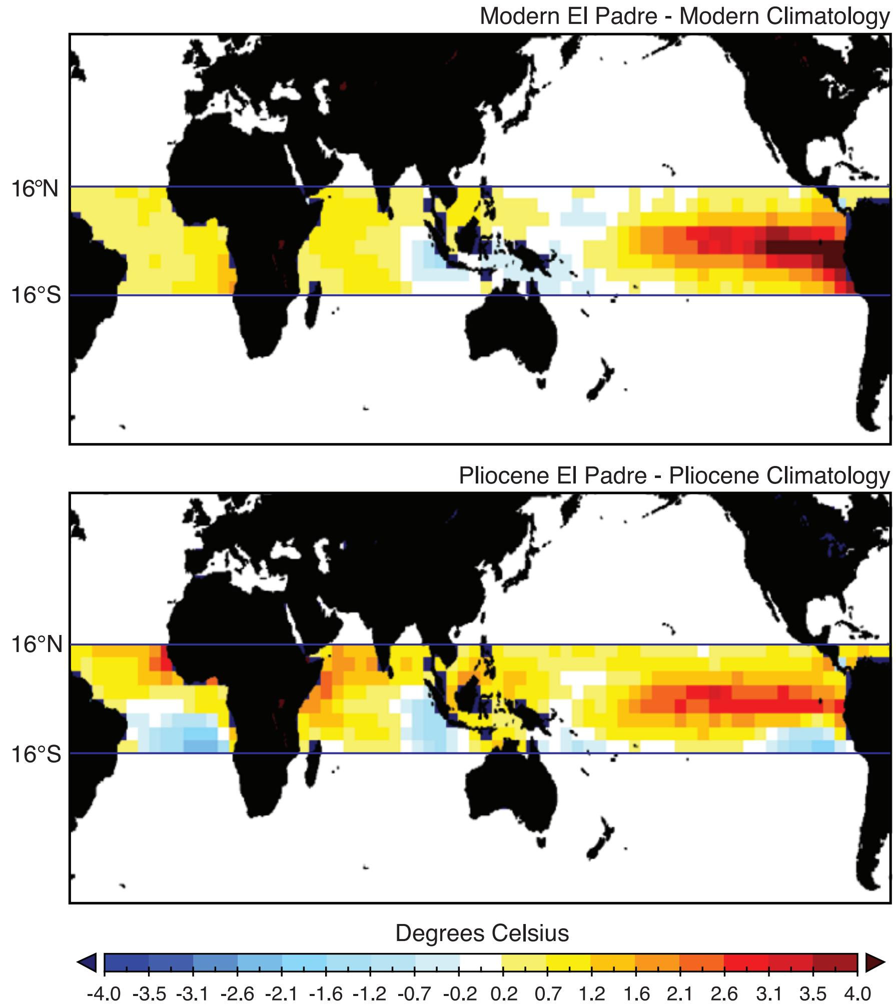

Figure 2. IOD/El Padre SST anomaly imposed on specified SSTs for (top) a modern monthly climatology and (bottom) PRISM2 SST reconstructions. The anomaly was imposed over the tropics from 16°N to 16°S. Note both the strong El Padre and IOD features in the tropical Pacific and Indian ocean basins, respectively.

respectively (Figure 2). Last, for comparison purposes, ModNiño is a simulation of the 1997/1998 El Niño event, forced by observed monthly SSTs.

3.1. GISS Global Climate Middle Atmosphere Model Version 3

[16] For this study we used the Goddard Institute for Space Studies (GISS) Global Climate Middle Atmosphere Model version 3 (hereafter referred to as GCMAM3), which is described in detail by *Rind et al.* [2007]. For these experiments we employ the version with 23 layers in the atmosphere and a top at 0.001 mb ($\sim$80 km). GCMAM3, like most GCMs, calculates temperature, pressure, winds, and specific humidity, using the conservation equations for mass, energy, momentum and moisture. Unlike other GCMs, GCMAM3 uses a fourth-order differencing scheme in both the momentum and mass equations, and a quadratic-

Table 1. Boundary Conditions and Forcings

Simulation	SST Distribution	Ice Sheets	CO_2 Forcing (ppm)
Modern Control (ModControl)	1961–1990 monthly climatology	Modern	380
Modern IOD/El Padre (ModPadre)	1961–1990 monthly climatology with 1997/1998 tropical anomaly imposed	Modern	380
Pliocene Control (PlioControl)	PRISM2 data set	PRISM2[a]	380
Pliocene IOD/El Padre (PlioPadre)	PRISM2 data set with 1997/1998 tropical anomaly imposed	PRISM2[a]	380

[a]PRISM2 ice sheet distribution assumes a 50% reduction in the Greenland ice sheet, a 25% reduction in the East Antarctic ice sheets, and the full removal of the West Antarctic ice sheet, on the basis of the premise that global sea level was 25 m higher than present.

Table 2. Global SON Average Surface Air Temperatures and Anomalies

Simulation	Global SON Average Temperature (°C)	ΔT From ModControl (°C)	IOD/El Padre ΔT From Control (°C)
ModControl	13.31	-	-
ModPadre	13.36	0.05	0.05[a]
PlioControl	15.58	2.27	-
PlioPadre	16.02	2.71	0.44[b]

[a]Compared to ModControl.
[b]Compared to PlioControl.

upstream scheme for heat and moisture advection. These schemes implicitly enhance absolute model resolutions of $4° \times 5°$ (latitude × longitude) to $1.3° \times 1.6°$ [see *Schmidt et al.*, 2006]. The radiation physics include all key trace gas constituents (CO_2, CH_4, N_2O, CFCs, and O_3) and aerosols (natural and anthropogenic), and is capable of simulating the effects of large forcing changes in constituents such as volcanic aerosols and greenhouse gases. In addition, a gravity wave drag parameterization incorporates the effects of flow over topography, wind shear and convection. Results from previous versions of the GISS Middle Atmosphere Model are widely published in major scientific studies [e.g., *Balachandran and Rind*, 1995; *Shindell et al.*, 2001; *Rind et al.*, 2001a, 2001b; *Rind et al.*, 2005] and the model has been shown to be robust for extreme palaeoclimate scenarios [*Rind et al.*, 2001a].

3.2. Results and Findings From Climate Model Simulations

[17] Table 2 shows the global September/October/November (SON) average surface air temperatures and anomalies for the listed simulations. Our modern El Niño simulation produced a surface air temperature increase consistent with observed surface air temperature increases at the end of 1997 and early 1998. However, our ModPadre simulation produced a negligible increase of 0.05°C. Both Pliocene simulations produced a warming of between 2°C and 3°C, which is consistent with proxy data implications. Interestingly, the PlioPadre simulation produced a warming from the PlioControl simulation that was an order of magnitude greater than that produced by the ModPadre from the ModControl simulation.

[18] In order to evaluate how well GCMAM3 could produce realistic El Padre conditions, we examined its ability to reproduce the similar El Niño phenomenon. This ModNiño simulation yielded both temperature and precipitation results consistent with observations in regions known to have robust El Niño teleconnections. Warming is reproduced over Alaska, northwestern United States, northern South America, northern and central Africa, the Indian Ocean region and western Europe (Figure 3a). Cooling was produced over Australia, which is inconsistent with observations [*Curtis et al.*, 2001; *Curtis and Adler*, 2003]; however, GCMAM3 also produced a dipole precipitation feature in the Indian Ocean (Figure 3d), increased rainfall over the central Pacific, along the U.S. west coast and over the Atlantic Ocean, and drying over Indonesia, all patterns consistent with November 1997 observations [*Hansen et al.*, 1999].

3.2.1. Significant Surface Air Temperature Findings

[19] ModPadre also displays a temperature distribution more consistent with observed El Niño teleconnections, where the most significant similarities include warmer temperatures over Alaska and northern South America, cooling over the southern United States, and a warming over Japan (Figure 3a). The cooling over the southern and western United States and the warming over Alaska are significant for they lie outside the SST "forcing" area, i.e., the imposed warm SST anomaly between 16°N and 16°S.

[20] Both the PlioControl and PlioPadre showed warming in the high latitudes, and more so in the Northern Hemisphere than in the Southern Hemisphere, a pattern consistent with proxy data (PRISM2) [*Ager et al.*, 1994; *Leopold and Liu*, 1994]. PlioControl showed little change in the tropics aside from cooling across Eastern Africa, the Middle East, and India related to changes in orography (PRISM2 topography versus modern) (Figure 3b). The PlioControl simulation also shows a cooling over northern South America, particularly on the western coast, which is inconsistent with proxy data suggesting increased temperatures [*Haywood et al.*, 2005]. PlioPadre preserved the cooling over these regions from PlioControl, but also produced significant warming in the tropics that accompanied the SST forcing (Figure 3c). PlioPadre also depicted a cooling over the southern United States that is consistent with proxy data, but was not present in the PlioControl simulation [*Graham*, 1989; *Dowsett and Poore*, 1990; *Cronin and Dowsett*, 1990; *Forester*, 1991; *Cronin*, 1991; *Thompson*, 1991, 1996].

3.2.2. Significant Precipitation Findings

[21] ModPadre rainfall patterns (Figure 3d) are consistent with observed El Niño distributions: increased rainfall over the southern United States and northwestern South America, and drying over northeastern South America. A dipole feature in the Indian Ocean is strongly apparent where East Africa receives increased rainfall and Indonesia experiences increased aridity. Although temperature teleconnections manifested at higher latitudes, such as the warming over Alaska described above, most of the changes in precipitation patterns are confined to the tropics where the SST anomalies were applied.

[22] PlioControl also indicates a dipole feature over the Indian Ocean region (Figure 3e), independent of an IOD/El Padre SST forcing. There is increased rainfall across northern South America, which is only partially consistent with Pliocene proxy data indicating wetter conditions in the northwest and a transition to more arid conditions in the northeast; again, most of the teleconnections seem to be isolated to the tropics [*Hovan*, 1995; *Nesbitt and Young*, 1997; *Saez et al.*, 1999]. There is no increased precipitation over the western and southern United States, a result inconsistent with the available terrestrial proxy data [*Graham*, 1989; *Forester*, 1991; *Cronin*, 1991; *Thompson*, 1991, 1996].

[23] The PlioPadre simulation intensifies those rainfall patterns (Figure 3f) shown in PlioControl, but with significant differences. The IOD feature is enhanced, increased aridity over Indonesia is more widespread, and the locus of increased precipitation over the western equatorial Pacific is larger and has moved closer to the equator. There is also increased rainfall over the southern and western coasts of

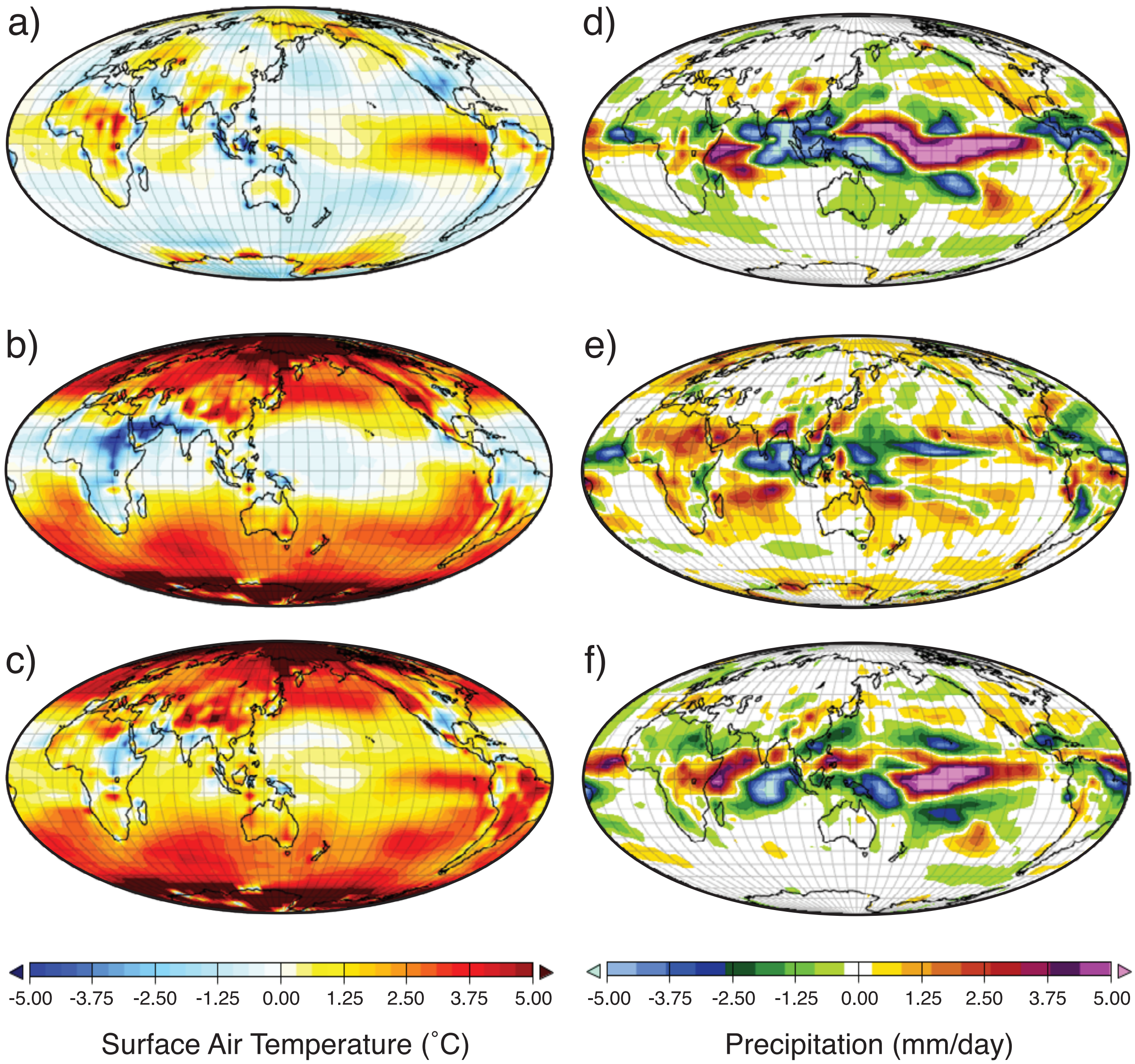

Figure 3. SON average surface air temperature anomalies for the (a) Modern El Padre, (b) Pliocene Control, and (c) Pliocene El Padre simulations. Note the cooling over the southern United States and the dipole feature over the Indian Ocean region in Figures 3a and 3c. SON average precipitation is also shown for the (d) Modern El Padre, (e) Pliocene Control, and (f) Pliocene El Padre simulations. The dipole precipitation pattern over the Indian subcontinent is shifted northward in Figure 3e, in contrast to the more equatorially located dipole features in Figures 3d and 3f.

the United States, and over western South America and the mid-Atlantic Ocean. In contrast, the Amazon basin experiences amplified drying.

4. Atmospheric Circulation Under El Padre Conditions

4.1. El Padre Mode

[24] El Padre is partly characterized as a (permanent) decrease in the sea surface temperature gradient between the eastern and western equatorial Pacific [*Ravelo*, 2008], similar to modern El Niño events. However, the physical mechanisms that sustain an El Padre and the resulting changes in atmospheric circulation are likely to be different from those associated with an El Niño, given the El Padre's nontransient nature.

[25] The El Padre, like a typical El Niño event, moves the locus of tropical atmospheric convection from the western tropical Pacific to a more central/eastward tropical Pacific location. This shift in convection yields increased rainfall along the west coast of South America, and increased aridity over large areas of the Indian Ocean basin. When an El Niño occurs, large-scale subsidence of warm air also results in the attenuation of monsoonal rainfall over the

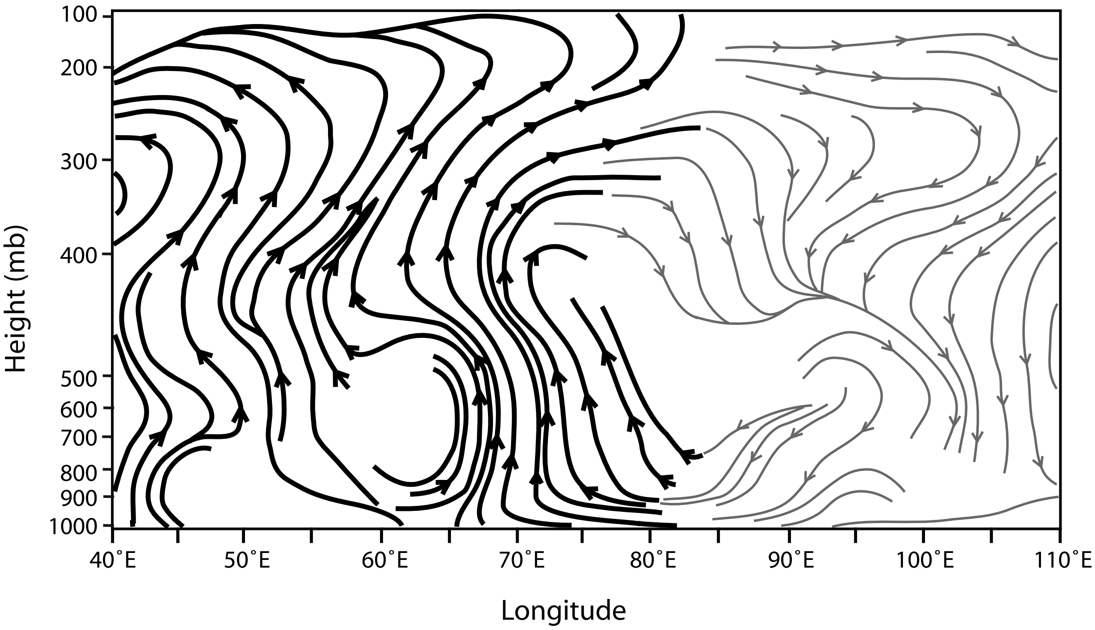

Figure 4. Anomalous Walker circulation during Indian summer monsoon for combined IOD and El Niño phenomenon. Bold lines indicate rising motion; gray lines indicate subsidence. Note the rising motion extends over northwestern India (approximately 70°E longitude). Modified from *Ashok et al.* [2004].

Indian subcontinent; but like an El Niño event itself, the attenuation effect is transient.

4.2. Indian Ocean Dipole Mode

[26] *Molnar and Cane* [2007] drew attention to the marked similarity between Pliocene paleoclimate proxy data and the impacts of the 1997/1998 El Niño event. In addition, there may also have been increased precipitation in the western Indian Ocean region during the Pliocene [*Hamilton and Taylor*, 1991; *Hill*, 1995; *Leakey et al.*, 1996], as was the case during the 1997/1998 El Niño. This increase in precipitation over India during 1997/1998 likely resulted from a combination of Indian Ocean Dipole (IOD) and El Niño influences on rainfall patterns, since increased rainfall over India is not characteristic of an El Niño event alone.

[27] The IOD is characterized by the episodic establishment of a strong warm-cool SST gradient across the equatorial Indian Ocean, and manifests during boreal summer, autumn and winter. Anomalous air-sea interactions lead to a shoaling thermocline and cooler SSTs in the eastern part of the basin, and a deepening thermocline along with warmer SSTs in the western part of the Indian Ocean. These warmer SSTs lead to increased convection over a broad region, bringing excess rain to East Africa, parts of the Middle East, and northwestern India. A basin-wide anomalous Walker cell is established (Figure 4), bringing subsidence and drier conditions to Indonesia, and exacerbating any existing drying conditions caused by a concurrent El Niño, as was the case for the 1997/1998 El Niño event.

[28] If Pliocene precipitation patterns were similar to that of 1997/1998, then an IOD feature should also have been present. *Vecchi and Soden* [2007] found a tendency toward such a combined permanent IOD/El Niño–like state in various global warming scenarios.

[29] When the two events occur together, as they did in 1997/1998, the IOD alleviates the drying effects of El Niño over the Indian subcontinent, producing a near-normal to above-normal summer monsoon rainfall [*Webster et al.*, 1999]. In essence, the rising motions associated with the anomalous convection over the western Indian Ocean dominate over the weaker El Niño subsidence (Figure 4). Recent data studies also suggest that the locus of anomalous convection associated with El Niño is shifting further east and south of its normal location, so subsidence over the Indian subcontinent is shifting as well (though Indonesia is still affected).

4.3. Rossby Waves and High-Latitude Teleconnections

[30] Convection and vertical motion balances heating in tropical regions, leading to divergence in the tropics and convergence in the subtropics at higher atmospheric levels (~200 mb height). This movement imparts energy that gives rise to planetary waves, or Rossby waves, which are capable of propagating to higher latitudes provided the background wind flow at intervening latitudes is coming from the west. (Easterly winds have the effect of deflecting the waves back to the equator, preventing poleward propagation).

[31] Rossby waves associated with an El Niño (or an El Padre) event are associated with an equatorward shift in the jet stream and midlatitude storm tracks, bringing increased rainfall to lower latitudes, as well as warmer conditions and

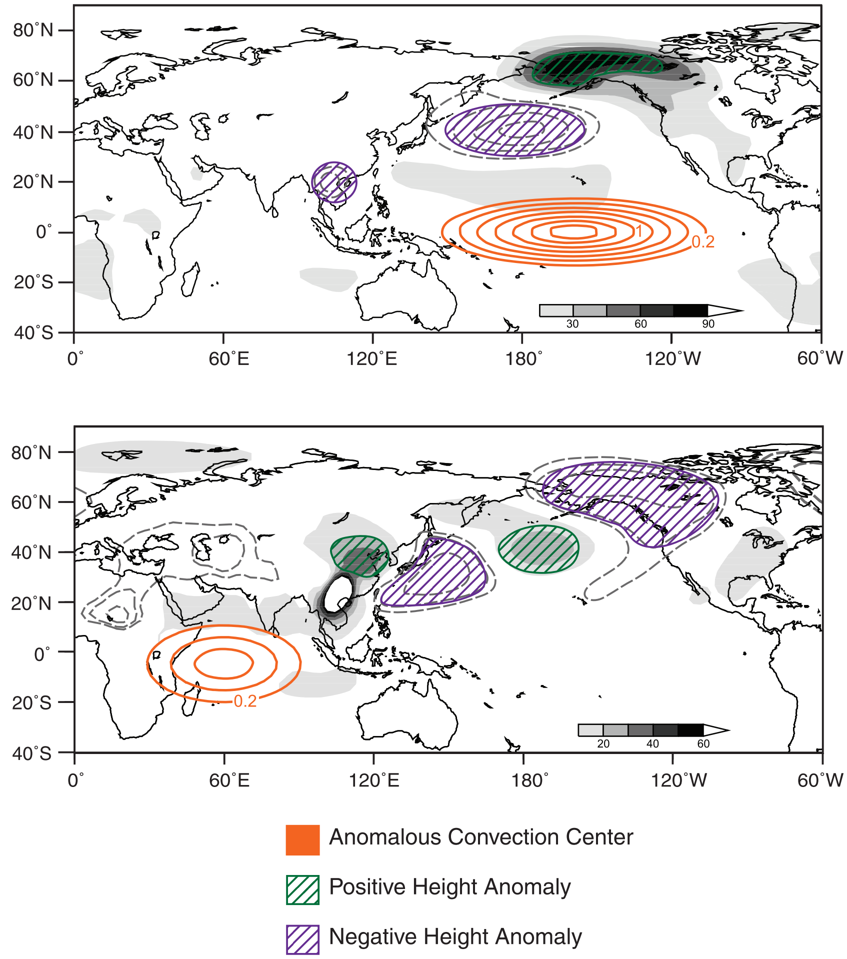

Figure 5. Height anomalies caused by anomalous convection centers in (top) the central tropical Pacific Ocean and (bottom) the western tropical Indian Ocean, both components of the IOD/El Padre condition (adapted from *Annamalai et al.* [2007]). The original study examined the effects of Indian Ocean SST anomalies on precipitation over the Pacific and North America. Gray shading (dashed contours) indicates positive (negative) perturbation height response (in m); orange contours indicate convection centers defined by diabatic heating anomalies (contour interval is 0.2 K d^{-1}). Areas of agreement with the current study are shown by the green shading (positive height anomalies) and purple shading (negative height anomalies).

positive atmospheric height anomalies over the Alaskan region (Figure 5). Typical El Niño teleconnections occur during the late fall and early winter, when cooler atmospheric temperatures give rise to a westerly background wind flow. Warmer summer time temperatures, however, have more easterly flow patterns, preventing extratropical teleconnections.

[32] In contrast, studies have shown that Rossby waves propagating from anomalous IOD convection in the western Indian Ocean basin are associated instead with cooler conditions and negative height anomalies over Alaska. Interactions between the Rossby waves emanating from concurrent El Niño and IOD conditions may actually have a canceling effect in which the positive and negative height anomalies destructively interfere with each other, provided they are of the same magnitude. However, if a combined IOD/El Padre state were to exist in a generally warmer climate, the background wind flow in the low to midlatitudes may behave more like modern boreal summer conditions, only year-round. The consequent easterly flow would then prevent the poleward propagation of waves generated by either phenomenon.

[33] The ModPadre sensitivity experiment exhibits strong warming and increased rainfall over Alaska, suggesting an equatorward shift in the jet stream and storm tracks to a position over the southern United States. These responses imply that teleconnections emanating from the Pacific component of the El Padre dominate over those from the IOD. Furthermore, any canceling effect of Rossby waves that a concurrent IOD might contribute appears to be weak and/or negligible, highlighting the importance of the relative magnitudes of each features' convective center.

[34] The PlioPadre experiment also shows increased precipitation over the southern United States and a warming over Alaska. Attribution of Alaskan warming to Rossby waves from the tropical Pacific is made difficult by other high-latitude forcings imposed by the PRISM2 boundary conditions. Yet the increased precipitation over the southern United States suggests a shift in the storm tracks via Rossby wave forcing, which defies our expectation that the generally warmer Pliocene climate would produce a background wind field inhibiting this propagation. It is possible that other circulation mechanisms may contribute to the transfer of convective energy out of the tropics, and that the high-latitude response may still be governed by the El Padre feature even if not directly through Rossby wave propagation. A more extensive investigation of the Rossby wave forcing and other atmospheric circulation features in our simulations, and how the specific characteristics of atmospheric energy transfer could relate to Pliocene warmth, is currently in progress and will be the focus of another study.

5. Discussion of Results

5.1. Simulated IOD/El Padre Condition and Its Effect on Pliocene Warmth

[35] The negligible difference in global surface air temperature between the ModPadre and ModControl simulations suggests that confining our SST anomaly between 16°N and 16°S limited the tropical contribution to global warming (+0.05°C). A simulation forced by a more latitudinally expansive Pacific SST anomaly would likely yield something closer to the 0.54°C global temperature increase produced in our Modern El Niño simulation.

[36] The net temperature impact of the IOD/El Padre condition was smaller than anticipated for ModPadre, with a global SON average temperature increase of just 0.05°C over ModControl (see Table 2). In comparison, the +0.44°C ΔT observed in PlioPadre compared to PlioControl is similar to the ΔT produced by ModNiño compared to ModControl (+0.54°C). This effect may be related in part to a lack of cryospheric feedbacks in the Pliocene. In addition, the global warming boost provided by the IOD/El Padre in PlioPadre corrects a greater-than-expected amount of cooling observed over the Middle East and India in PlioControl, thus providing a better match with proxy data in that region. It is worth noting that the degree of PlioPadre warming would be significant in modern contexts, in which temperatures have risen by about 0.74°C over the last 100 years [*Intergovernmental Panel on Climate Change*, 2007]. Although *Haywood et al.* [2007] regarded a ~0.5°C contribution from an El Padre condition as not significant to overall Pliocene warming, their comments are in the context of assessing the direct forcing of a 2–3°C warming, whereas our point here is to emphasize the significance of the eventual state of tropical Pacific and IOD ocean temperatures from the perspective of global warming in general.

[37] In the case of PlioPadre, then, we consider an IOD/El Padre condition, with a magnitude similar to that of the 1997/1998 El Niño/IOD event, to be a significant contributor to global warmth, accounting for ~20% of the 2–3°C warming over modern suggested by proxy data for the Pliocene warm interval. The order of magnitude difference in global warming produced by PlioPadre versus ModPadre (when each are compared to their own control run) suggests that the already warmer PlioControl climate amplified the tropical response, permitting the IOD/El Padre anomalies to contribute more to overall warmth. This overall warming may have been achieved through an increased water vapor feedback, which has a nonlinear greenhouse gas contribution, or perhaps through alternate mechanisms related to changes in atmospheric heat transport or an altered background circulation pattern. A more complete analysis of the impact of an IOD/El Padre state on tropical and extratropical atmospheric dynamics is in preparation and will be presented separately.

[38] On a more regional basis, PlioControl and PlioPadre are consistent with terrestrial proxy data showing warming concentrated at higher latitudes, so the specific contribution of an IOD/El Padre to high-latitude warming will require additional experiments and iterative comparison with proxy data to unravel fully. However, there were significant differences between these simulations in the tropics, where PlioPadre showed greater consistency with Pliocene terrestrial proxy data. PlioPadre produces both cooler temperatures and more widespread precipitation across the southern and western United States, which was absent in the PlioControl simulation. Interestingly, the PlioControl simulation also shows a dipole precipitation pattern over the Indian subcontinent; it is translated poleward from its characteristic equatorial location and is weaker, but its presence in the atmospheric response to Pliocene SST conditions in the control run suggests that this precipitation feature may be a preferred state for the Pliocene driven in part by high-latitude conditions.

[39] The regional effects we see in our IOD/El Padre simulations (warming over Alaska and northwest North America, cooling in the southern United States) appear to signify a "permanent" reorganization of atmospheric circulation under warm tropical conditions that is conducive to extratropical and high-latitude El Niño–like teleconnections, even given a forcing region constrained to between 16°N and 16°S.

5.2. Simulated IOD/El Padre Condition and Its Effect on Pliocene Rainfall

[40] Since our ModPadre and PlioPadre simulations were forced with November 1997 IOD/El Niño SST anomalies, and rainfall patterns can be highly dependent on SST distribution, it is not surprising that both ModPadre and PlioPadre rainfall patterns reflect those observed in November 1997. It is worth noting that ModPadre's rainfall responded strongly and produced large changes of both signs, even though the temperature response to the SST anomalies was small. This suggests that even smaller changes in temperature, if sustained, can be associated with large, permanent changes in precipitation patterns because the overlying atmospheric response is tightly coupled to the SST forcing region.

[41] The intensification of tropical precipitation we find in PlioPadre compared to PlioControl is logical, given that the

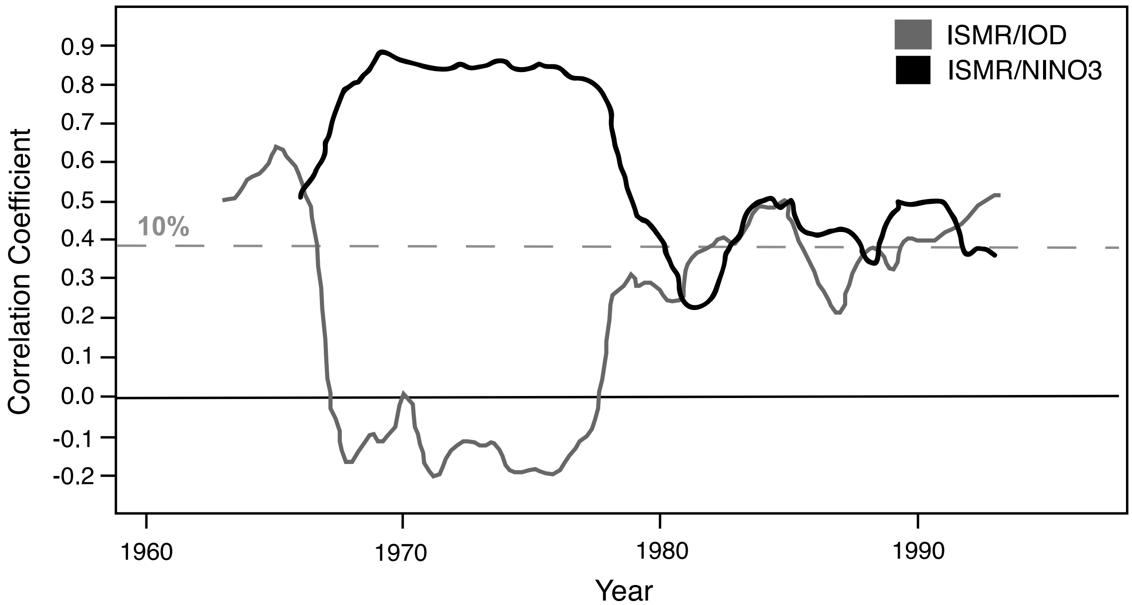

Figure 6. Correlation plot of the Indian Monsoon Summer Rainfall (ISMR) with the IOD index (gray) and with the NINO3 index (black). Note the decreasing/increasing correlation with NINO3/IOD since the late 1970s. Adapted from *Ashok et al.* [2001].

IOD/El Padre condition was confined to the tropics. However, the effects of the IOD/El Padre seem more limited than we might have expected; the IOD convection center over the western tropical Indian Ocean dominates over any anomalous subsidence attributed to the Pacific sector warming, so the IOD feature dominates the Indian Ocean region rainfall variability. In fact, the occurrence of the IOD rainfall in both PlioControl and PlioPadre suggests that the feature might actually arise independently from the El Padre. This phenomenon is consistent with observational studies of the modern IOD showing increasing/decreasing influence of the IOD/El Niño on Indian monsoonal rainfall (Figure 6) [see also *Krishna Kumar et al.*, 1999], as well as projections that the influence of the Pacific ocean basin on the Indian Ocean region will weaken with a warming climate [*Saji et al.*, 1999].

[42] The modern and proxy rainfall data, combined with our modeling results, imply that Pacific sector (El Padre) SST anomalies will be less influential in the Indian Ocean region under a warm climate than SSTs in the Indian Ocean basin itself. The IOD is then one of the dominant sources of variability. Additionally, our simulations suggests that the El Padre feature may have a different degree of influence on the tropics compared with higher latitudes.

5.3. IOD/El Padre-Induced Changes to Atmospheric Circulation

[43] As described above, both the Pacific sector and IOD convection centers should produce Rossby waves that propagate to higher latitudes, provided there is a westerly background wind field. From our ModPadre simulation, we see a clear warming over Alaska, which is associated with Rossby waves that emanate from the Pacific sector and cause positive height anomalies over the region. This suggests that even if both features occur together, the Rossby waves from the Pacific convection center dominate over those produced by the IOD; whether this is primarily due to a difference in magnitude between the features, or if the IOD convection center is embedded in a background wind flow that prevents high-latitude propagation, is not certain. In addition, more experimentation and analysis will be required to evaluate the role of Rossby waves in the PlioPadre simulation, as the already warmer high latitudes obscure the contribution from the tropics. Future work following this study will assess the various aspects of high-latitude wave propagation from these features to determine their contribution under Pliocene conditions.

[44] In order to fully assess the role of the Indian Ocean under Pliocene conditions, and determine if a permanent IOD feature was a characteristic of the Pliocene, it would be helpful to accumulate more proxy data from the Indian Ocean region, in terms of both terrestrial indication of temperature and precipitation and also SSTs that specifically span the tropical Indian Ocean.

6. Conclusions

[45] While the high-latitude warming in the Pliocene simulations remains the main contributor to the total increase in globally averaged surface air temperature, it does not alone reproduce the various regional subclimates as indicated by terrestrial proxy data. Therefore, in addition to the high-latitude warming effects, a combination of both the El Padre and Indian Ocean Dipole (IOD) appears to be necessary to reproduce temperature and precipitation patterns more consistent with the global distribution of Pliocene proxy data. We

made no initial a priori assumptions about the robustness or validity of the paleoceanographic data used, but our conclusions are supportive of the existing SST data, and indeed provide motivation for further targeted paleoceanographic surveys in both the Indian Ocean and western Pacific.

[46] Our simulations produce cooling and increased precipitation over the southern and western United States, and warming over Alaska, where abundant data are available. These results have not been obtained in Pliocene simulations forced only by PRISM2 boundary conditions, which include warming at high latitudes but show little change in the tropical SSTs.

[47] In all of our simulations, the IOD dominates the precipitation response over East Africa, the Arabian Sea, and the Indian subcontinent. The El Padre by itself produces drying over Indonesia and increased rainfall over western South America, but does not suppress the Indian monsoon when the IOD is also present. In the extratropics of the Northern Hemisphere, Rossby waves generated in our IOD/El Padre simulations propagate from the Pacific Ocean sector to influence high-latitude climates, apparently overwhelming the potential canceling effects of waves generated further west by the IOD.

[48] In our Pliocene control simulations, which use the standard PRISM2 boundary conditions, there is substantial warming at high latitudes and a precipitation dipole feature develops over the Indian subcontinent. This makes it apparent that an IOD could have been forced by the substantial changes that existed at high latitudes in the Pliocene, independent from any El Padre condition that developed under warm climate conditions. It also suggests that we cannot yet definitively state whether tropical changes drove climate change at high latitudes, or if the reverse was true.

[49] Regardless, the role of the Indian Ocean Dipole as both forcing and feedback during the Pliocene has not been fully explored. The few data that do exist from the region support the presence of a strong IOD during the Pliocene. However, collection of additional terrestrial data from Indonesia, northern Australia, and East Africa is needed to assess the dipole's impact on Pliocene atmospheric circulation, and direct confirmation of the existence of a Pliocene IOD would be possible with additional SST proxies from the Indian Ocean region. Ultimately, the combination of better terrestrial and marine proxy data with GCM analyses will provide greater insight into the role of tropical SSTs in warming climates.

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